Light dark matter in NMSSM and implication on Higgs phenomenology

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Abstract

For the experimental search of neutralino dark matter, it is important to know its allowed mass and scattering cross section with the nucleon. In order to figure out how light a neutralino dark matter can be predicted in low energy supersymmetry, we scan over the parameter space of the NMSSM (next-to-minimal supersymmetric model), assuming all the relevant soft mass parameters to be below TeV scale. We find that in the parameter space allowed by current experiments the neutralino dark matter can be as light as a few GeV and its scattering rate off the nucleon can reach the sensitivity of XENON100 and CoGeNT. As a result, a sizable parameter space is excluded by the current XENON100 and CoGeNT data (the plausible CoGeNT dark matter signal can also be explained). The future 6000 kg-days exposure of XENON100 will further explore (but cannot completely cover) the remained parameter space. Moreover, we find that in such a light dark matter scenario a light CP-even or CP-odd Higgs boson must be present to satisfy the measured dark matter relic density. Consequently, the SM-like Higgs boson h_{SM} may decay predominantly into a pair of light Higgs bosons or a pair of neutralinos so that the conventional decays like $h_{SM} \to \gamma\gamma$ is much suppressed.

PACS numbers: 12.60.Jv,11.30.Qc,12.60.Fr,14.80.Cp

Introduction: Experiments for the underground direct detection of cold dark matter $\tilde{\chi}$ have recently made significant progress. While the null observation of $\tilde{\chi}$ in the CDMS and XENON100 experiments has set rather tight upper limits on the spin-independent (SI) cross section of $\tilde{\chi}$-nucleon scattering [1, 2], the CoGeNT experiment [3] reported an excess which cannot be explained by any known background sources but seems to be consistent with the signal of a light $\tilde{\chi}$ with mass around 10 GeV and scattering rate around 10^{-40} cm^2. Intriguingly, this range of mass and scattering rate is compatible with the dark matter explanation for both the DAMA/LIBRA data and the preliminary CRESST data [4]. So far, due to the inconsistency of the CoGeNT result with the CDMS or XENON result, it is premature to draw any definite conclusion about the existence or nonexistence of a light $\tilde{\chi}$. However, considering much effort is being paid on the search of a light $\tilde{\chi}$ in experiments, it is theoretically important to check the possible new physics prediction for a light $\tilde{\chi}$ and examine its related phenomenology (such as the Higgs boson search) at the LHC. In this work we will focus on low energy supersymmetry, where the lightest neutralino $\tilde{\chi}_1^0$ serves as the dark matter candidate, and perform an intensive study of the light $\tilde{\chi}_1^0$ scenario.

The most popular model for low energy supersymmetry is the minimal supersymmetric standard model (MSSM). In this model, we find from our scan that the neutralino $\tilde{\chi}_1^0$ must be heavier than about 28 GeV. The main reason for the absence of a lighter $\tilde{\chi}_1^0$ is its dominant annihilation channel is $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}$ through s-channel exchange of the pseudoscalar Higgs boson (A) and the measured dark matter relic density requires $m_A \sim (90\text{--}100)$ GeV and $\tan\beta \sim 50$, which is in conflict with the constraints from the LEP and B physics experiments [5–7]. Here we emphasize that for the above region the effects of the charged Higgs on $B \to X_s\gamma$ are unacceptably large, and even with a fine tuning of the contributions from the stop/chargino diagrams, such large effects cannot be reduced to an acceptable level. Our results for the MSSM are in agreement with [7], but differ from [8] in which the considered constraints, such as the invisible Z-decay and the productions of neutralinos or Higgs bosons at LEP II, are weaker than in our study. Our conclusion also differs from [9] because we used more accurate formula in calculating the process $B \to X_s\gamma$ [10]. Since the neutralino dark matter in the MSSM cannot be so light as suggested by the CoGeNT data (albeit not corroborated by XENON100 or CDMS), here we do not present our MSSM results in detail.

Another popular model for low energy supersymmetry is the next-to-minimal supersym-

metric standard model (NMSSM) [11] which extends the MSSM by adding one gauge singlet chiral superfield $\hat{S}$. This model is well motivated because it provides a solution to the μ-problem and the little hierarchy problem the MSSM suffers from. For this model we perform an intensive scan over its parameter space by assuming all the relevant soft mass parameters below TeV scale and considering various experimental constraints. We find that in this model the neutralino dark matter can be as light as a few GeV and its spin-independent scattering cross section with the nucleon can reach the sensitivity of CoGeNT and XENON100.

We emphasize that our study is not restricted to explain any special experimental results like the CoGeNT or DAMA/LIBRA data. Instead, we aim to investigate the characteristics of a light $\tilde{\chi}_1^0$, such as its lower mass bound and scattering rate off the nucleon, and also examine the related Higgs phenomenology at the LHC.

The NMSSM: We start our analysis by recapitulating some basics of the NMSSM. Its superpotential and the associated soft-breaking terms in the Higgs sector are given by [11]

$$\mathbf{W} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3, \tag{1}$$

$$V_{soft} = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2$$
$$+ (\lambda A_\lambda H_u H_d S + h.c.) + \left(\frac{\kappa}{3} A_\kappa S^3 + h.c.\right), \tag{2}$$

where H_d, H_u and S denote scalar components of the superfield $\hat{H}_d$, $\hat{H}_u$ and $\hat{S}$, respectively. After using the minimization condition of the Higgs potential, this sector is described by three dimensionless parameters ($\tan\beta$, λ, κ) and three dimensionful parameters (μ, A_λ, A_κ). Due to the imposed Z_3 symmetry, the superpotential does not contain dimensionful parameters and thus all dimensionful parameters are generated by the soft-breaking masses which, as required by the electroweak symmetry breaking, should be naturally below TeV scale [11]. Other free parameters are the same as in the MSSM, i.e., the soft masses for sfermions and gauginos as well as the trilinear soft couplings.

Due to the presence of $\hat{S}$, the NMSSM predicts five neutralinos, three CP-even Higgs bosons ($h_{1,2,3}$) and two CP-odd Higgs bosons ($a_{1,2}$) [11]. In general, the neutralino mass eigenstates are the mixture of the MSSM neutralino fields and the singlino field which is the fermion component of $\hat{S}$; the CP-even (odd) Higgs mass eigenstates are similarly the mixture of the CP-even (odd) MSSM Higgs fields and the real (imaginary) part of the scalar component of $\hat{S}$. An important feature of the NMSSM is that one of the CP-even (odd)

Higgs bosons may be singlet-like and thus can be very light [11]. This feature is particularly useful for light $\tilde{\chi}_1^0$ scenario since it opens up new important annihilation channels for $\tilde{\chi}_1^0$, i.e., either into a pair of h_1 (or a_1) or into a pair of fermions via s-channel exchange of h_1 (or a_1) [7, 12, 13]. For the former case, $\tilde{\chi}_1^0$ must be heavier than h_1 (a_1); while for the latter case, due to the very weak couplings of h_1 (a_1) with $\tilde{\chi}_1^0$ and with the SM fermions, a resonance enhancement (i.e. m_{h_1} or m_{a_1} must be close to $2m_{\tilde{\chi}_1^0}$) is needed to accelerate the annihilation. So a light $\tilde{\chi}_1^0$ should be necessarily accompanied by a light h_1 or a_1 to provide the required dark matter relic density.

Now we discuss how to get a light h_1 or a_1 in the NMSSM. A light a_1 can be easily obtained when the theory approaches to the $\mathrm{U}(1)_R$ or $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry limit, which can be realized by setting the product κA_κ to be negatively small [11]. In contrast, a light h_1 can not be obtained so easily, but, as shown below, it can still be achieved by somewhat subtle cancellation via tuning the value of A_κ. We note that for any theory with multiple Higgs fields, the existence of a massless Higgs boson implies the vanishing of the determinant of its squared mass matrix and vice versa. For the NMSSM, at tree level the parameter A_κ only enters the mass term of the singlet Higgs bosons and thus the determinant $(\mathrm{Det}\,\mathcal{M}^2)$ of the mass matrix for the CP-even Higgs bosons depends on A_κ linearly [11]. When other relevant parameters are fixed, one can then obtain a light h_1 by varying A_κ around the value $\tilde{A}_\kappa$ which is the solution to the equation $\mathrm{Det}\,\mathcal{M}^2 = 0$. In practice, one must include the important radiative corrections to the Higgs mass matrix, which will complicate the dependence of $\mathcal{M}^2$ on A_κ. However, we checked that the linear dependence is approximately maintained by choosing the other relevant parameters at the SUSY scale, and one can solve the equation iteratively to get the solution $\tilde{A}_\kappa$.

Numerical scan and results: In order to study light $\tilde{\chi}_1^0$ scenario in the NMSSM, we scan randomly over the parameters in the neutralino and Higgs sectors by requiring $0 \leq \lambda, \kappa \leq 0.7$, $1 \leq \tan\beta \leq 60$, $0 \leq \mu, A_\lambda, M_2 \leq 1$ TeV and $0 \leq M_1 \leq 100$ GeV. Here the ranges of λ, κ and $\tan\beta$ are determined by the perturbativity of the theory [11], the ranges of μ and A_λ are suggested by the electroweak symmetry breaking, and the narrow range of bino mass M_1 is chosen to facilitate a light $\tilde{\chi}_1^0$. Since the gluino mass and the soft parameters in the squark sector affect little on the properties of $\tilde{\chi}_1^0$, we set all of them to be 1 TeV. As for the soft slepton parameters, since they influence the muon anomalous magnetic moment a_μ

which in turn can limit the important parameter $\tan\beta$, we assign them a common scale $m_{\tilde{l}}$ and vary it below TeV scale.

Since a light $\tilde{\chi}_1^0$ is very likely to be accompanied by a light h_1 or a_1, we perform two independent scans aiming at a light h_1 and a light a_1 respectively. For the light h_1 case, we vary A_κ around $\tilde{A}_\kappa$ which is obtained by solving the equation $\mathrm{Det}\,\mathcal{M}^2 = 0$; while for the light a_1 case, we simply vary A_κ in the range $[-200, 0]$ GeV.

In our scans, we require all dimensionful parameters in the Higgs potential like m_{H_u} and m_{H_d} below TeV scale and keep the parameter points which yield $m_{\tilde{\chi}_1^0} \leq 20$ GeV. The constraints considered in our scan are the following [14]: (1) We require $\tilde{\chi}_1^0$ to account for the dark matter relic density $0.105 < \Omega h^2 < 0.119$; (2) We require the NMSSM contribution to explain the deviation of the muon a_μ, i.e., $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (25.5 \pm 8.0) \times 10^{-10}$, at 2σ level; (3) The LEP-I bound on the invisible Z-decay, $\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 1.76$ MeV, and the LEP-II upper bound on $\sigma(e^+ e^- \to \tilde{\chi}_1^0 \tilde{\chi}_i^0)$, which is 5×10^{-2} pb for $i > 1$, as well as the lower mass bounds on sparticles from direct searches at LEP and the Tevatron; (4) The constraints from the direct search for Higgs bosons at LEP-II, including the decay modes $h \to h_1 h_1, a_1 a_1 \to 4f$, which limit all possible channels for the production of the Higgs bosons; (5) The constraints from B physics observables such as $B \to X_s\gamma$, $B_s \to \mu^+\mu^-$, $B_d \to X_s\mu^+\mu^-$, $B^+ \to \tau^+\nu$, $\Upsilon \to \gamma a_1$, the a_1–η_b mixing and the mass difference ΔM_d and ΔM_s; (6) The constraints from the precision electroweak observables such as ρ_{lept}, $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, m_W and R_b; (7) The constraints from the decay $\Upsilon(1S) \to \gamma h_1 \to \gamma(\pi^+\pi^-, K^+K^-)$, $\Upsilon(nS) \to \gamma h_1 \to \gamma\mu^+\mu^-$ ($n = 1, 2, 3$) and the Tevatron search for a light Higgs boson via 4μ and $2\mu 2\tau$ signals [15]. The constraints (1–5) have been encoded in the package NMSSMTools [16]. We use this package in our calculation and extend it by adding the constraints (6, 7). As pointed out in [15], the constraint (7) is important for a light Higgs boson.

In Fig. 1 we display the surviving parameter samples, which are simultaneously projected on the σ^{SI}-m_χ plane in the left frame and the σ^{SI}-m_{h_1} or σ^{SI}-m_{a_1} plane in the right frame. In our calculation we use the formula in [19] for the scattering rate and choose $f_{T_u}^{(p)} = 0.023$, $f_{T_d}^{(p)} = 0.034$, $f_{T_u}^{(n)} = 0.019$, $f_{T_d}^{(n)} = 0.041$ and $f_{T_s}^{(p)} = f_{T_s}^{(n)} = 0.020$ as input. Note that, motivated by recent lattice simulation [20], we take a very small value of f_{T_s} and consequently our estimation of the rate is rather conservative.

The left frame of Fig. 1 clearly shows that in the NMSSM the neutralino dark matter can be as light as several GeV, while the right frame of Fig. 1 shows that such a light neutralino
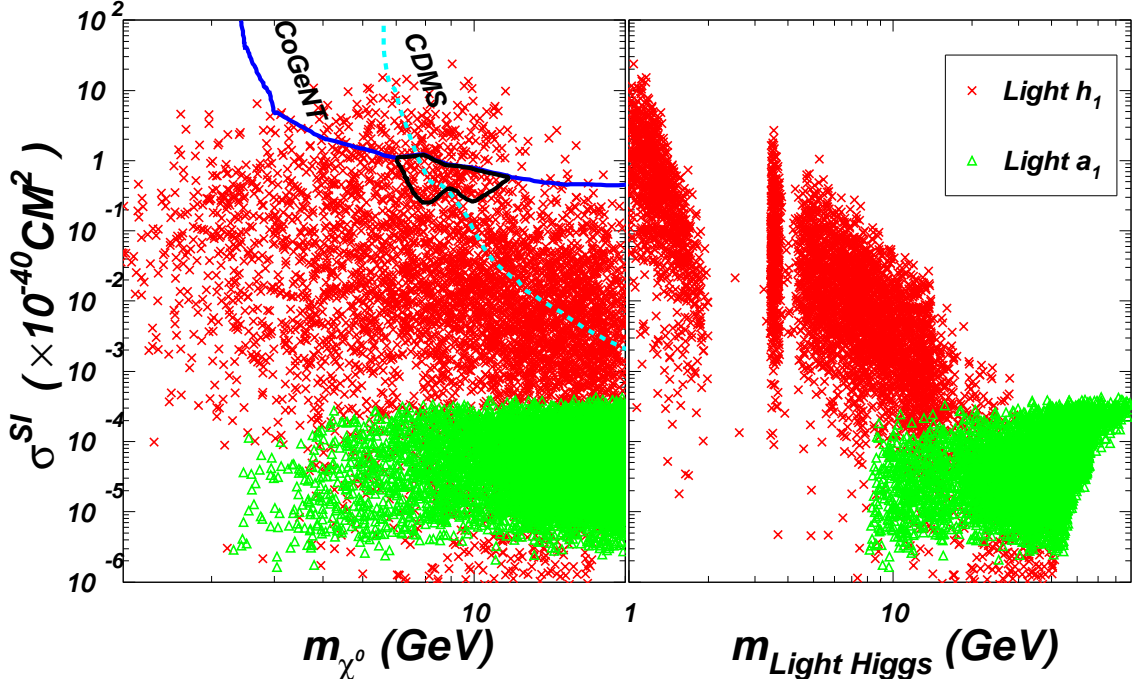
FIG. 1: The scatter plots of the parameter samples which survive all constraints. The samples denoted by '×' (red), which are simultaneously projected on the σ^{SI}-m_χ plane in the left frame and the σ^{SI}-m_{h_1} plane in the right frame, are characterized by a light h_1; while the samples denoted by '△' (green), which are simultaneously projected on the σ^{SI}-m_χ plane in the left frame and the σ^{SI}-m_{a_1} plane in the right frame, are characterized by a light a_1. The curves are the limits from CoGeNT [3], CDMS [1] and XENON100 [2], while the contour is the CoGeNT-favored region [3]. The future XENON100 (6000 kg-days exposure) sensitivity is also plotted [17].

is accompanied by either a light h_1 or a light a_1. So the surviving samples were classified into two sets, characterized respectively by a light h_1 and a light a_1. In both the light-h_1 case and the light-a_1 case the surviving samples give a bino-dominant $\tilde{\chi}_1^0$ and correspondingly a small M_1 ($\lesssim 30$ GeV). The allowed regions for other parameters are listed in Table I. We see that the value of μ is not so large (below 300 GeV in light-h_1 case and 350 GeV in light-a_1 case) because a low μ can enhance the coupling of $\tilde{\chi}_1$ to h_1 and a_1 to get the correct relic density. Also we see a moderately loose bound on m_{a_1} (we checked that among the surviving samples about 2% have $m_{a_1} \geq 60$ GeV). This is due to a possibly large $\tan\beta$, which can enhance the couplings of a_1 to the SM fermions so that m_{a_1} may deviate from $2m_{\tilde{\chi}_1^0}$ significantly. In the light-h_1 case, about 75% of the surviving samples are found to satisfy $m_{h_1} \leq m_{\tilde{\chi}_1^0}$, in which the annihilation mode $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_1 h_1$ plays a crucial role in getting the required dark matter

TABLE I: The allowed parameter ranges for the light-h_1 case (first row) and light-a_1 case (second row). The dimensionful parameters μ, A_κ and m_{h_1,a_1} are in unit of GeV.

λ	κ	$\tan\beta$	μ	A_κ	m_{h_1,a_1}
0.15–0.7	0–0.5	1–7	130–300	−600–0	$1\lesssim m_{h_1}\lesssim 45$
0.15–0.5	0.1–0.7	8–60	150–350	−80–0	$8\lesssim m_{a_1}\lesssim 80$

relic density. In contrast, in the light-a_1 case most surviving samples are found to satisfy $m_{a_1} \geq m_{\tilde\chi_1^0}$, in which the dominant annihilation channel of dark matter is $\tilde\chi_1^0\tilde\chi_1^0 \to a_1^* \to f\bar{f}$.

From Fig. 1 we see that the scattering rate of the light dark matter can reach the sensitivity of XENON100 and, consequently, a sizable parameter space is excluded by the XENON100 (2011) data [2]. The future XENON100 experiment (6000 kg-days exposure) [17] can further explore (but cannot completely cover) the remained parameter space. Note that in the light-h_1 case the scattering rate can be large enough to reach the sensitivity of CoGeNT and can cover the CoGeNT-favored region. The underlying reason is that the χ-nucleon scattering can proceed through the t-channel exchange of the CP-even Higgs bosons, which can be enhanced by a factor $1/m_{h_1}^4$ for a light h_1 [12]; while a light a_1 can not give such an enhancement because the CP-odd Higgs bosons do not contribute to the scattering in this way. We noticed that the studies in [6, 18] claimed that the NMSSM is unable to explain the CoGeNT data because they did not consider the light-h_1 case.

Note that the light-h_1 samples are separated into three regions of m_{h_1}, as shown in the right frame of Fig. 1. This is due to the *combined* constraints from the dark matter relic density and the processes $\Upsilon(1S) \to \gamma h_1$ (with $h_1 \to \pi^+\pi^-, K^+K^-, \mu^+\mu^-$), $B_d \to X_s\mu^+\mu^-$ and $p\bar{p} \to h_{SM} \to 4\mu$(or $2\mu2\tau$) at the Tevatron, which tightly limited the couplings and mass of h_1. For example, since in this case h_1 mainly acts as the product of dark matter annihilation, its coupling to $\tilde\chi_1^0$ must be moderately large to get the correct relic density, while its couplings to the SM fermions and h_{SM} must be small to suppress the rates of the processes mentioned above [15]. The situation is different for the light-a_1 case, where the relic density and the LEP search for Higgs boson require $m_{a_1} > 8$GeV. For such a 'heavy' a_1 the above mentioned low energy processes give no stringent constraints and thus the light-a_1 samples are not separated into different regions of m_{a_1}, as shown in the right frame of Fig. 1.

Implication on Higgs physics: In the NMSSM the light $\tilde\chi_1^0$ scenario may predict rather

peculiar Higgs phenomenology due to the presence of the light particles. Among the predicted Higgs bosons, the SM-like Higgs boson $h_{\rm SM}$, defined as the CP-even Higgs boson with largest couplings to Z^0 pair, will be the most important one to be searched at the LHC since it mainly responsible for electroweak symmetry breaking. So we focus on $h_{\rm SM}$ in our following discussion.
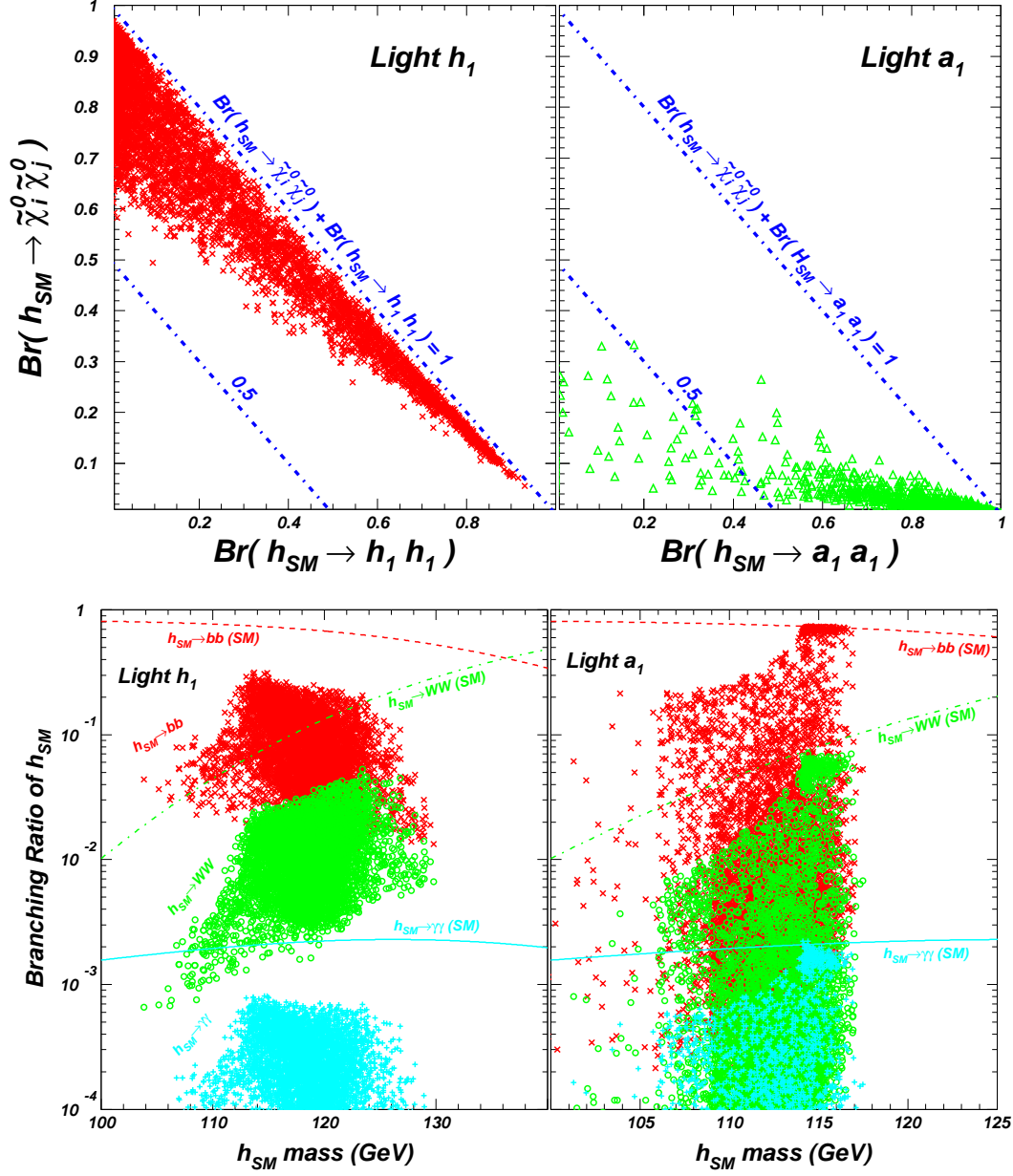

FIG. 2: Same as Fig.1, but showing the decay branching ratios of the SM-like Higgs boson $h_{\rm SM}$. Here $Br(h_{\rm SM} \to \tilde{\chi}_i^0 \tilde{\chi}_j^0)$ denotes the total rates for all possible $h_{\rm SM} \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$ decays.

In the light $\tilde{\chi}_1^0$ scenario, $h_{\rm SM}$ may decay exotically into $\tilde{\chi}_i^0 \tilde{\chi}_j^0$, $h_1 h_1$ or $a_1 a_1$, and conse-

quently the conventional decays are reduced. This feature is illustrated in Fig. 2, which shows that the sum of the exotic decay branching ratios may exceed 50% and the the traditional decays $h_{\rm SM} \to b\bar{b}, \tau\bar{\tau}, WW^*, \gamma\gamma$ can be severely suppressed. Numerically, we find that the branching ratio of $h_{\rm SM} \to b\bar{b}$ is suppressed to be below 30% for all the surviving samples in the light-h_1 case and for about 96% of the surviving samples in the light-a_1 case. For the remaining 4% samples in the light-a_1 case, due to the kinematical forbiddance of the decay $h_{\rm SM} \to a_1 a_1$, the ratio of $h_{\rm SM} \to b\bar{b}$ usually exceed 30% and may even approach its SM value ($\sim 70\%$). The samples with the ratio exceeding 65% are found to be characterized by $m_{a_1} > 58$ GeV, $m_{a_2} \geq 350$ GeV and $\tan\beta \geq 37$.

Another interesting feature shown in Fig. 2 is that, due to the open-up of the exotic decays, $h_{\rm SM}$ may be significantly lighter than the LEP bound. This situation is favored by the fit of the precision electroweak data and is of great theoretical interest [21].
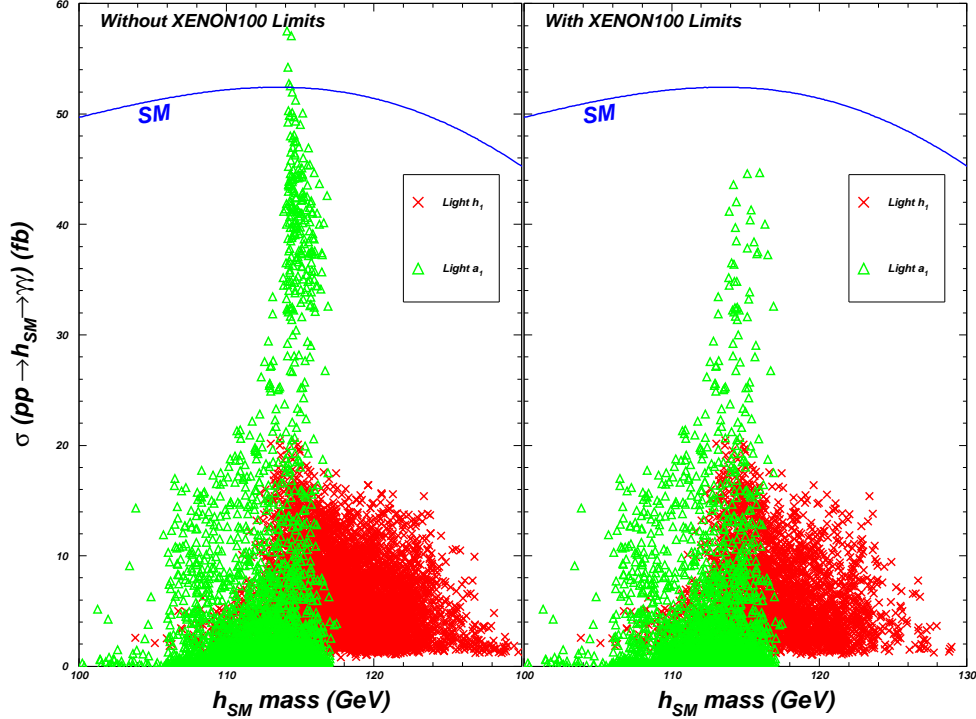

FIG. 3: Same as Fig. 1, but showing the diphoton production rate of the SM-like Higgs boson at the LHC.

Since the conventional decay modes of $h_{\rm SM}$ may be greatly suppressed, especially in the light-h_1 case which can give a rather large $\chi - N$ scattering rate, the LHC search for $h_{\rm SM}$ via the traditional channels may become difficult. Noting $h_{\rm SM}$ is bounded from above by about 130 GeV and hence its most important discovering channel at the LHC is the di-

photon signal, we show the di-photon rate at the LHC with $\sqrt{s} = 14$ TeV in Fig. 3. In calculating this rate, we used the narrow width approximation and only considered the leading contributions to $pp \to h_{\rm SM}$ from top quark, bottom quark and the squark loops.

Fig. 3 indicates that, compared with the SM prediction, the NMSSM rate in the light $\tilde{\chi}_1^0$ scenario is suppressed to be less than 20 fb for the light-h_1 case, and for the light-a_1 case most samples (about 96%) give the same conclusion. Since in the light-h_1 case the $\chi - N$ scattering rate can reach the CoGeNT sensitivity, this means that in the framework of NMSSM the CoGeNT search for the light dark matter will be correlated with the LHC search for the Higgs boson via the di-photon channel.

Note that, as shown in the left frame of Fig.3, a few samples can give a di-photon rate which is comparable with or even exceeds its SM prediction. We checked that these samples predict approximately same decay branching ratios of h_{SM} as the SM Higgs boson, and the excess is mainly due to the slight suppression of the width of $h_{SM} \to b\bar{b}$ so that $Br(h_{SM} \to \gamma\gamma)$ is enhanced. We also checked that the null result of the future XENON 6000 kg-days exposure will imply a Higgs di-photon signal below 20 fb at the LHC with 99% probability.

Finally, we point out that our light-h_1 scenario is different from the scenario considered in [15]. The basic ideas of [15] are: (1) Consider a special part in the parameter space, which is characterized by $\lambda, \kappa \to 0$ and $A_\lambda \simeq \mu \tan\beta$ so that $\text{Det}\, \mathcal{M}^2 \simeq 0$ to get a light h_1; (2) Consider a nearly decoupled $\hat{S}$ so that the singlino serves as the dark matter with its annihilation and its scattering with the nucleon proceeded mainly by exchanging a light singlet a_1 and h_1 respectively. Such a treatment obviously has the unnaturalness problem in electroweak symmetry breaking since the condition $A_\lambda \simeq \mu \tan\beta$ usually pushes the soft mass m_{H_d} in Eq. (2) up to several TeV. We note the results of [7] also suffer from this problem. In our scenario, however, we keep the naturalness by requiring all soft masses to be below TeV scale.

Conclusion: We scrutinized the light neutralino dark matter scenario in the NMSSM by scanning over the parameter space with all the relevant soft masses below TeV scale. We found that in the parameter space allowed by current experiments the neutralino dark matter can be as light as a few GeV and its scattering rate with the nucleon can reach the sensitivity of XENON100 and CoGeNT (the CoGeNT signal can be explained). The present XENON100 and CoGeNT data can exclude a large parameter space, and the future

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6000 kg-days exposure of XENON100 can further explore (but cannot completely cover) the remained parameter space. In such a light dark matter scenario, a light CP-even or CP-odd Higgs boson must be present to satisfy the measured dark matter relic density. As a result, the SM-like Higgs boson $h_{\rm SM}$ may dominantly decay into a pair of light Higgs bosons or a pair of neutralinos, and consequently the conventional decays like the di-photon signal at the LHC will be much suppressed.

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